A METHOD FOR EXHAUST GAS TREATMENT IN A SOLID OXIDE FUEL CELL POWER PLANT

BACKGROUND

5   *Field of the Invention*

The invention relates to methods for anode exhaust treatment in solid oxide fuel cell power plants where the air stream and fuel stream is kept separate throughout the system. Particularly, the invention relates to solutions

10   for recovering and recycling the unspent fuel from the anode fuel exhaust gas.

Background information

An increasing demand for electric power combined with increasing environmental awareness has initiated extensive

15   research for developing cost effective and environmentally friendly power generation. Although several renewable power sources are available, only nuclear and hydrocarbon fuelled power plants can supply the bulk of the power being demanded. Nuclear power plants suffer from safety risks and

20   problematic radioactive waste disposal. Future development of nuclear power plants seems very limited, mostly due to lack of political acceptance. Thus, power plants based on fossil fuels are called upon to fill most of the energy gap. However, a continuous development of scientific data

25   on the Greenhouse effect and political agreements such as the Kyoto protocol from 1997, is generating an increasing push towards limiting and reducing greenhouse gas emissions. As a result of this trend, several countries seek to limit their carbon dioxide (CO_2) emissions and

30   establish annual maximum emission levels. In this endeavour, CO_2 emissions from fossil fuel power plants is a main concern since such plants are a considerable source of CO_2 emissions. As an example, about one third of the US CO_2 emissions come from such power plants. Typically, the CO_2

35   emissions from a natural gas based power plant producing 3

TWh per year would be in the order of 1.1 million tons per year [ref. Gassm.]. It is therefore desired to develop efficient fossil fuel power plants with capture of CO_2 that subsequently can be sequestered. Sequestration of the CO_2, produced from a large-scale power plant, will most likely be achieved by injection as gas, liquid or hydrates into subterranean formations or into deep seawater. A commercial value for the produced CO_2 may be obtained when used for enhanced oil recovery in producing oil fields.

Several processes/concepts for power production from fossil fuels with greatly reduced CO_2 emissions are known in the art. These processes produce concentrated and pressurised CO_2 suitable for sequestration or industrial usage. The methods for recovering the CO_2 from natural gas based power production may be divided into three main categories, i.e.:

1) Pre-combustion decarbonisation
2) Oxyfuel or oxygen-fired combustion
3) Post-combustion CO_2 -capture

Precombustion involves a "decarbonisation" of the fuel prior to usage in a standard Gas Turbine Combined Cycle power plant (GTCC) plant or alternative power producing technology based on fossil fuels. As a typical example, such a process would include reformation, water gas shift, and CO_2 removal by chemical absorption using conventional amine systems. The resulting fuel gas is hydrogen-rich and may be used in some gas turbines. An advantage of this concept is that it is essentially based on a series of known unit operations. There is however only a small number of gas turbines available that may use the hydrogen rich gas as fuel. Therefore, unless modifications/qualifications of other gas turbines are made, this concept will not be available at different scales. The most economical scales for the components are large and the specific costs and efficiencies will suffer as the scale is reduced. Another disadvantage of applying conventional CO_2 removal solutions

in precombustion is that they are operated at low temperature, requiring cooling and reheating of the gas due to the CO_2 removal. This concept will have an efficiency that is lower than for a standard GTCC plant or other alternative technology. The precombustion are typically considered combined with other less developed power producing technologies such as fuel cells. Also, other emerging CO_2 removal technologies are typically considered in the literature such as CO_2 selective membranes, hybrid sorbent/membrane systems, physical or chemical sorbents.

The Oxyfuel category includes concepts supplying the oxygen used to oxidise the natural gas in such a manner that nitrogen does not enter the reaction zone. The combustion products are, in principle, only CO_2 and H_2O. The water is removed by cooling / condensation of the combustion products and the result is a nearly pure CO_2 gas stream. One way of keeping nitrogen away from the reaction zone is to produce oxygen in a conventional cryogenic air separation unit prior to combustion. Other variations include usage of high temperature ceramic oxygen transfer membranes to produce oxygen or supply of oxygen by means of a metallic oxygen carrier (chemical looping combustion). One example of a oxyfuel concept is a process based on oxygen production in a conventional air separation unit(s) (ASU), combustion in a specialised gas turbine, utilisation of heat in a steam bottoming cycle and recycle of gas turbine exhaust (CO_2 / H_2O) for temperature control. For plant sizes below app. 200 MW, the cryogenic air separation units must be sized down from the optimum scale. This gives a considerable cost penalty in the 10-50 MW scale. Further, a smaller scale gas turbine with higher specific cost and lower performance must be assumed. Also the use of CO_2/H_2O recycle to control the temperature will consume energy at the expense of total efficiency. Both investment cost and energy consumption are very high for generation of oxygen at the purity and quantity required in Oxyfuel cycles. Most of the prior art has required the use of a source of highly

concentrated oxygen, ref. US pat. no. 5 724 805, US pat.
no. 5 956 937 and US pat. no. 5 247 791. In order to reduce
the cost of oxygen, it is a goal to include the use of
oxygen selective ion transport membranes in Oxyfuel cycles.
This implies that a way to achieve a positive oxygen
partial pressure differential and the required temperature,
must be found. A conventional heat recovery system is
proposed to utilize the heat emitted by the cycle. These
are costly, and more economical ways for the utilization of
this heat energy are demanded.

Postcombustion is based on cleaning of the exhaust from a
GTCC plant or other power producing technology based on
fossil fuels. The exhaust stream typically contains roughly
3 - 4 vol% CO_2 that may be removed from the exhaust in a
wet scrubbing process involving chemical absorption using
an amine based absorbent. Heat (steam from the power plant)
is required to disassociate the CO_2 from the absorbent. The
result is an almost 100% pure CO_2 gas at atmospheric
pressure that can be pressurised for transport and
disposal. This technology can be retrofitted to existing
plants and also it may be "turned off" without stopping the
power production from the plant. However, the low
concentration of CO_2 requires large gas handling systems
and the treated exhaust gas will still contain
approximately 15 % of the CO_2, also NO_x and some amines will
be present in the exhaust gas. The efficiency will be lower
than for a standard GTCC plant or alternative technologies
due to the energy needed to separate the CO_2. Alternative
less developed CO_2 separation technologies that typically
would be considered are chemical or physical sorbents or
CO_2 selective membranes.

The technologies described above will typically have
electrical efficiencies less than 50 %. In addition, many
of them will still emit about 10-15 % of the CO_2. It is
therefore a desire to develop fossil fuel driven power
plants with CO_2 capture that is highly efficient, emits

less CO_2 and has a lower cost of energy than prior art technology.

Two separation technologies not mentioned in the description above are of particular interest for present

5   invention, i.e. hydrogen selective membranes and cryogenic CO_2 separation.

Various types of hydrogen selective membranes are generally known. Hydrogen separation membranes can typically be categorized into two main types:

10   *Microporous types*, which comprise polymeric membranes and porous inorganic membranes

Dense types, which comprise self-supporting non-porous metal, non-porous metal supported on a porous substrate such as porous metal or ceramic, and mixed ionic and

15   electronic conduction materials.

The microporous type of membranes generally has a limited selectivity, while the dense type has "infinite" selectivity.

Polymeric membranes typically cannot be used at operating

20   temperatures above 250°C due to lack of stability and they also are incompatible with many chemicals that can be present in the feed stream. The polymeric membranes also suffer from a lack of selectivity of hydrogen over other gases and the product gas therefore is relatively impure.

25   Micro porous inorganic membranes are typically made of silica, alumina, titania, molecular sieve carbon, glass or zeolite. All are fabricated with a narrow pore size distribution and exhibits high hydrogen permeability but relatively low selectivity due to the relatively large mean

30   pore diameter. Typical operating temperature for a silica membrane would be <300~400°C.

Dense membranes normally consist of palladium or palladium alloys or mixed ionic and electronic conducting materials. The Pd and Pd-alloy based membranes typically consist of a thin non-porous or dense film or foil of Pd or Pd-alloys coated on a porous support of ceramics or porous stainless steel. The thickness of the Pd or Pd alloys film is at present typically 70 to 100 μm for commercial membranes (small scale) and due to the high price of Pd this makes these membranes very expensive and the thickness also results in low permeance. It is essential to have very thin Pd or Pd-alloy films/foils to get a high permeance and an acceptable price. Supported Pd or Pd-alloy membranes of much thinner film thickness are often reported in the literature. Typical operating temperatures for Pd and Pd-alloys membranes are in the range 200-500°C and even higher temperatures have been stated (up to 870°C).

Mixed ionic and electronic conducting (MIEC) membranes have mostly been studied for oxygen separation as described earlier. MIEC membranes for hydrogen separation is far less developed, also compared to Pd-alloy membranes and microporous membranes. These membranes are however expected to develop fast due to the large efforts in developing similar oxygen separating MIEC membranes. The MIEC hydrogen separating membranes function by transferring hydrogen as protons and electrons through the dense mixed ceramic material. Typical operating temperatures for the mixed ionic and electronic conducting membranes is 600-1000°C.

Cryogenic technology, cooling to temperatures between -40 and -55°C, for separating CO_2 from a gas stream is conventional technology and very well known. This technology is also used for cooling and liquefaction of CO_2. The separation is performed at elevated pressure in order to avoid solid CO_2 and to increase the required operating temperature. The feed gas to be separated is compressed and dehydrated (to avoid ice) and cooled. After cooling most of the CO_2 is liquefied and the mixture can

easily be separated. Separation can be performed by a
simple gravity-based separator or a column could be used in
order to obtain a purer CO_2 or less CO_2 in the cleaned gas.

5   In recent years many solid oxide fuel cell based power
plant concepts of substantial size (above 1 MW) have been
presented [ref]. These studies are often based on operation
at pressure, typically 3-15 bars. This increases the
electrical efficiency and also makes hybrid systems
including gas turbines attractive. Typically, the air is
10   compressed and preheated before entering the SOFC, where
electrical power is produced in electrochemical reactions
with the fuel and the generated heat is partly absorbed by
the air stream. Subsequently, the hot oxygen depleted air
is typically mixed with the spent fuel leaving the anode
15   side and the mixture is combusted to further increase the
gas temperature before the heated gas is expanded in a
turbine producing additional electricity. The pressurised
solid oxide fuel cell/gas turbine hybrid systems appears to
be very attractive for power production due to the high
20   electrical efficiency that can be expected for these
systems, typically more than 70 % (in the multi-MW range).
Examples of typical pressurised solid oxide fuel cell/ gas
turbine hybrid concepts that are described in literature
can be found in the following references [1, 2, 3, 4, 5].
25   These systems does however all emit the combusted fossil
fuel as CO_2 to the atmosphere.

For these typical solutions both precombustion
decarbonisation and postcombustion CO_2 capture methods can
be applied in order to make the concept "zero emission",
30   but this will be at the expense of efficiency loss and
increased cost as for the other solutions presented.

However, a solid oxide fuel cell system can be classified
as an oxyfuel system since the oxygen is transferred
through the fuel cell wall to the anode side, leaving the
35   nitrogen on the cathode side, provided that the air stream

and the fuel stream is kept separated after the electrochemical reaction.

A so-called zero emission solid oxide fuel cell power pilot plant of this type is developed by Shell together with
5   Siemens Westinghouse Power Corporation. The goal is to use fossil fuels for power generation with high efficiency and without emission of CO_2 to the atmosphere. The pilot plant will be operated at atmospheric pressure and will be located at Kollsnes in Norway.

10 There are two major differences to the zero emission solid oxide fuel cell power plant concept compared to those described above. 1) A seal is applied keeping the cathode air stream separated from the anode fuel gas in such a manner that the two streams are not mixed after the fuel
15 cell reactions. 2) An afterburner is applied in order to further utilise the unreacted fuel leaving the anode side of the fuel cell. Two types of afterburners has been suggested: 1) An additional SOFC unit operated to convert the majority of the remaining fuel and producing some
20 additional electricity, and 2) using an oxygen transport membrane (OTM) to provide the oxygen for combusting the remaining fuel. The heat released can be used to generate steam for use in a steam turbine. Both he SOFC afterburner and an OTM will be very expensive solutions and give
25 limited additional electricity output.

Prior art describes recycle of anode gas in fuel cell systems, ref. US pat no. 5,079,103. The described systems use pressure swing adsorption (PSA) for separation of CO_2 from H_2 and CO in the anode exhaust from a SOFC stack. The
30 PSA system operates by adsorption of CO_2 from the anode exhaust. However, the CO_2 content in this stream is substantial and the required PSA system will increase the overall cost and complexity.

It is thus desired to find simple and preferably cheap
solutions for utilising the remaining unreacted fuel in the
anode exhaust gas for additional power production
maintaining a high electrical efficiency and simultaneously
5 produce clean and preferably pressurised CO_2 stream.

Brief Description of the Invention

The subject invention presents a method for solving the
problems described above. The present invention relates to
solid oxide fuel cell systems having a seal system that
10 keeps the air and fuel stream separated. Particularly, it
relates to the fuel cell anode side exhaust gas treatment
in such a system, and more particularly, to exhaust gas
treatment methods that separate and recycle the unspent
fuel to the main SOFC. The invention is most suitable for
15 SOFC systems that operate at elevated pressures and are
integrated with a gas turbine.

The air is compressed and preheated before it enters the
fuel cell stack at the cathode side. Fossil fuel,
preferably natural gas, is pretreated to remove poisons
20 such as sulphur compounds before it is converted by steam
reforming to a mixture of H_2, CO, CO_2 and H_2O. This mixture
enters the fuel cells at the anode side. Oxygen in the air
is transferred through the fuel cell wall and reacts
electrochemically with H_2 and CO, generating electricity
25 and heat. The cathode and anode gas is kept separate by a
seal system.

The oxygen depleted air on the cathode side absorbs heat as
it passes through the fuel cell on the cathode side. The
hot oxygen depleted air is subsequently expanded in a
30 turbine producing additional electricity, heat exchanged
with the incoming air and vented.

The anode exhaust can preferably partly be recirculated to
the reformers in order to provide the steam required for

the steam reforming (otherwise steam must be supplied to
the reformers). The remaining fraction of the anode exhaust
gas is further treated in two optional ways: 1) in a
hydrogen membrane unit and 2) in a cryogenic separation
unit.

Using option 1), a high temperature hydrogen membrane unit,
the hydrogen in the exhaust gas is transferred through the
membrane by a partial pressure difference and as hydrogen
is removed from the feed gas side, the water-gas-shift
reaction converts more of the remaining CO to hydrogen (the
membrane must catalyse water-gas-shift reaction or a
catalyst has to be included). A sweep gas such as steam may
be applied on the permeate side to increase the driving
force. The anode exhaust gas consists mostly of CO_2 and H_2O
after the membrane separation (some H_2 and CO and also N_2
will be present). The water is easily removed and the
result is a concentrated CO_2 stream at roughly the
operating pressure. The permeate hydrogen rich gas is
compressed and recirculated to the fuel cell or reformer,
where it is efficiently utilised to generate electricity.

Using option 2), the cryogenic method the anode exhaust gas
is cooled, water is removed before the gas is compressed,
cooled, further dried and CO_2 is separated by a gravity-
based separator or a column at moderately low temperatures.
The resulting gas contains mainly hydrogen, CO some N_2 and
an amount of CO_2 that depends on the separation
temperature. The resulting liquid stream is pressurised CO_2
and can be transported by ships or trucks if desired.

Both of these options are advantageous alternatives to
pressure swing adsorption for pressurised SOFC systems. By
usage of hydrogen selective membranes, hydrogen is
recovered from the fuel cell anode exhaust. The fuel stack
should in this case be pressurised in order to obtain as
great driving pressure as possible over the hydrogen
selective membranes. The membranes may operate at elevated

temperature and the amount of hydrogen that has to be removed is relatively small compared to the amount of CO_2 in the anode exhaust. Additionally, the CO_2 may pass the membranes on the retentive side without large pressure

5   drops. The resulting system is simple and has a very good potential for cost savings. This will in particular apply if the CO_2 is to be captured and exported from the power plant by pipeline. In this case some hydrogen is permitted in the retentive gas, allowing a non-perfect hydrogen split

10 and selection of a small hydrogen membrane area. These factors enable hydrogen selective membranes, which now rarely is used, to be competitive when used in a pressurised fuel cell system with CO_2 capture.

Another advantageous option is usage of a cryogenic,

15 gravity based separation process. The overall system will then include a combination of a high temperature SOFC system with a low temperature cryogenic separation process. A detailed investigation focused on the required purity of the recovered hydrogen and CO will reveal that a

20 substantial amount of diluents are permissible. This enables a relatively simple cryogenic separation process. This option may easily produce liquefied CO_2 ready for transportation by trucks or ships and is therefore particularly beneficial if CO_2 is to be captured and

25 exported and the SOFC stack is pressurised.

An important advantage of potentially cheap and efficient separation/recycle processes, is that it will be possible to reduce the fuel utilisation in the main SOFC stack. Reduction of the fuel utilisation will increase the voltage

30 and hence increase the SOFC efficiency further. Zero emission solid oxide fuel cell power plants based on the concepts of the present invention hold the promise of high efficiency power production from fossil fuels with CO_2 capture, much higher efficiency than can be expected for

35 other typical power production systems with CO_2 capture.

Another important advantage of the zero emission SOFC/gas turbine hybrid solution is the applicability also in the much lower MW range than would be preferred for many of the other CO_2 capturing solutions presented above.

5   The membranes of interest for the present invention are the high temperature hydrogen selective membranes. Particularly, hydrogen selective membranes including water-gas-shift activity are of interest. The major difference of the employment of H_2 selective membranes in the present

10 invention compared to other application is that it is used as an exhaust gas treatment method to recover unspent fuel. The embodiment of the present invention does not require a very pure hydrogen stream since CO is also a reactant for SOFC. Also, a certain amount of CO_2 can be tolerated

15 (trade-off with larger gas volumes). The present embodiment also allows for the use of a sweep gas, preferably steam, at the permeate side. There will also be relatively small amounts of hydrogen that are going to be recovered and this reduces the required membrane area needed. Another

20 advantage of the present application is that it leaves the CO_2 at high pressure while the hydrogen permeate gas looses pressure. The hydrogen stream flow rate is considerably smaller than the CO_2 stream, thus much less compression cost is required to compress the hydrogen compared to what

25 would be needed for the CO_2.

The combination of the cryogenic separation with the zero emission SOFC system provides a simple and elegant means of separating and recycling the unspent fuel. It is relatively cheap and consumes little additional energy.

30 Thereby, the subject invention presents methods that simplifies the anode gas treatment in SOFC cycles with CO_2 capture.

Brief Figure Description

Fig. 1 is a schematic of the main principles of the present
invention.

Fig. 2 is a schematic flow diagram of the present invention
showing the main parts of the power plant.

Fig. 3 is a schematic flow diagram of a specific embodiment
of the present invention using a cryogenic separation
process in a power plant.

Fig. 4 is a schematic flow diagram of a specific embodiment
of the present invention using a separation process based
on high temperature hydrogen selective membranes in a power
plant.

Fig. 5 is a schematic flow diagram of a specific embodiment
of the present invention using a separation process based
on high temperature hydrogen selective membranes in a power
plant, in which the recovered hydrogen is combusted to
increase the temperature of the oxygen depleted air.

The invention also allows production of heat and/or steam
usable for distribution to district heating or nearby steam
consumers.

Detailed Description

Referring now in detail to the figures of the drawings, in
which identical parts have identical reference symbols, and
first, particularly, to FIG 1. FIG.1. shows the main
principles of the present invention. The main SOFC stack 1,
is divided into an anode section 2 and a cathode section 3
by a sealing system 4. This seal system may be a steam
seal. Addition of steam, 5, is needed for this particular
seal. In order to simplify the schematic, the anode section
comprise of all needed reforming steps, as well as optional

internal recycle of part of the anode exhaust to the
reformers to provide steam required for the steam
reforming, or steam addition to the reformers if internal
recycle of fuel is omitted, in addition to the fuel cells
5   anode side. No details of the fuel cells are shown. In the
present example the fuel cells are of the tubular (one
closed end) solid oxide type. Poison-free fuel containing
the element carbon 102, typically natural gas, is fed to
the anode side 2, and compressed and preheated air 205 is
10 fed to the cathode side 3 of the main SOFC stack 1. The
reformed fuel is electrochemically reacted with oxygen from
the air on the anode side 2 of the fuel cell producing
electricity and heat. The electricity is typically
converted from DC to AC in an inverter 6 The anode exhaust
15 gas 301, typically consisting of H_2, CO ,CO_2 and H_2O is
further transferred to the separation process 302 where the
main aim is to separate the CO_2 and H_2O from the unspent
fuel. The recovered fuel 304 is typically recirculated to
the main fuel cell stack.

20 FIG. 2 is a schematic flow diagram of the present invention
showing the main parts of the power plant. A line
containing fuel 100, typically natural gas, is shown going
to a fuel pretreatment unit 101. This fuel pretreament unit
contains all necessary poison removal steps to produce a
25 fuel that is sufficiently clean to enter the reformer and
fuel cells in the main SOFC unit 1 through line 102.
Typically, the pretreatment unit would consist of
desulphurisation by one of the conventional methods known
to those skilled in the art. The cleaned fuel enters the
30 main SOFC stack and is converted as described for FIG. 1,
producing electricity and heat. The anode exhaust gas is
transferred through line 301 to the separation process 302
as described for FIG.1. The concentrated CO_2 stream 303
leaving the separation process is typically further
35 compressed in a conventional compression train 307 before
it is sent to sequestration 308. The recovered fuel 304 is
typically cooled 305 before it typically is recycled to the

main SOFC. The air stream 201 is compressed to the desired
operating pressure in a compressor 202, typically the
compressor part of a gas turbine. The compressed air 203 is
preheated in a heater 204 before it enters the cathode side
5   3 of the main SOFC. The air flowing through the cathode
side of the fuel cell absorbs heat and is vitiated in
oxygen. The heated and oxygen depleted air leaving the main
SOFC 206 is expanded in a turbine 207 producing additional
energy.

10   FIG.3 is a schematic flow diagram of a specific embodiment
of the present invention using a cryogenic separation
process in a power plant. The fuel pretreatment 101, main
SOFC 1 and gas turbine 201-209 units have already been
described above. The expanded air 208 is typically heat
15   exchanged with the incoming air 203 in a recuperator 204
before it is vented 209. In the present example, the fuel
100, typically natural gas, enters the fuel pretreatment
unit 101 at 8.5 bara and 20°C and is desulphurised by
passing through a fixed-bed absorbent system. After
20   desulphurisation, the gas 103 is mixed with the recycle gas
329 from the separation process. The mixture 104 is heat
exchanged 105 with the anode exhaust gas 301 to increase
the temperature to about 200°C. The preheated gas 106
enters the main SOFC 1 and is converted in several steps as
25   described previously. The anode exhaust gas leaves the main
SOFC stack at a temperature of about 800°C. The anode
exhaust gas typically consist of 3.0 % H_2, 1.6 % CO, 33.7 %
CO_2, 60.0 % H_2O and 1.8 % N_2. After heat exchange in 105,
the water is removed in a condenser or scrubber 310.
30   Additional coolers not shown are used to cool the gas. The
water 332 is sent to a water treatment unit and discarded
or used as feedwater in a steam system. The scrubbed gas
311 is compressed in a compressor 312 to a pressure of
about 23 bara. The compressed gas 313 is then cooled 314,
35   treated in a scrubber 316 and dehydrated 319 before it is
further cooled 321 to a temperature where a portion of the
CO_2 is in liquid form. This cooling is achieved by use of

conventional, closed, industrial refrigeration systems (not
shown in detail). The liquid CO_2 in stream 322 is separated
from the gases in a low temperature (-40- -55°C) gravity
based separator 323. In the specific example the
temperature is -50°C and the pressure is 22.5 bar. The gas
leaving the separator 327 is heated 328, and expanded
through a valve (not shown) to obtain the operating
pressure before it is mixed with the purified feed gas 103.
A small portion, typically 5%, of the recycled gas is
discarded in order to avoid build-up of non-combustible and
non-condensable gases, typically N_2. The recycled gas
typically consists of 32 % H_2, 15 % CO, 34 % CO_2 and 18% N_2.
The liquefied CO_2 324 from the separator 323 is sent to
storage 325 from which it can be transported by ship or
truck, or optionally sequestered by pipeline. The liquefied
CO_2 stream typically consists of more than 98 %CO_2. This
specific embodiment of the present invention typically has
a calculated electrical efficiency of around 60 % (ac/LHV).

FIG.4 is a schematic flow diagram of a specific embodiment
of the present invention using a separation process based
on high temperature hydrogen selective membranes in a power
plant. The fuel pretreatment 101, mixing with recycle gas
357 and conversion in main SOFC 1 is similar to the example
described in FIG. 2. The gas turbine unit 201-209 is also
described above. In the present example the anode exhaust
stream 301 enters a hydrogen selective membrane unit 350 on
the feed side at 6.7 bara. The temperature is dependent on
the membrane type selected and conventional cooling may be
used to achieve it. Hydrogen is transferred through the
membrane with a selectivity dependent on the membrane type.
In the specific example the membrane is operating at a
temperature of 600°C. The hydrogen rich permeate gas
typically contains 50 % H_2. Typically, the pressure on the
permeate side is close to ambient and a sweep gas 359
(preferably steam) is used to increase the driving force.
The hydrogen rich permeate gas 351 is cooled in a heat
exchanger 352 and water is removed by a condenser or

scrubber 354, before the scrubbed gas 355 is compressed 360
to the operating pressure in a multistage, inter cooled
compressor and mixed with the clean fuel 103. The retentate
gas 358 consists of CO_2, H_2O, small amounts of H_2, CO and N_2
5 and is heat exchanged in 105 before water is removed by a
condenser or scrubber 310. Additional coolers not shown are
used to cool the gas. The scrubbed, CO_2-rich gas 361 is
compressed 362, cooled 364, scrubbed 366 and dehydrated 368
before it is further compressed 370 to the desired pressure
10 for sequestration. The CO_2-rich gas produced in this system
typically has a composition of 96 % CO_2, 2 % H_2, 1% CO and
1 % N_2. The specific embodiment of the present invention
typically has a calculated electrical efficiency of around
60 % (ac/LHV).

15 FIG.5 is a schematic flow diagram of a specific embodiment
of the present invention using a separation process based
on high temperature selective membranes in a power plant
and with a specific use of the recovered hydrogen. The
process is as described for FIG.4, but with the following
20 exception. The recovered and compressed hydrogen 357 is
mixed with the oxygen depleted air 20 and combusted in
combustor 401, thereby increasing the temperature of the
resulting mixture of oxygen depleted air and steam 402
before entering the expander 207.